Results from Three Years of Ka-band Propagation Characterization at Svalbard, Norway

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***Abstract*— Over the next several years, NASA plans to launch several earth science missions which are expected to achieve data throughputs of 5-40 terabits per day transmitted from low earth orbiting spacecraft to ground stations. The current S-band and X-band frequency allocations in use by NASA, however, are incapable of supporting the data rates required to meet this demand. As such, NASA is in the planning stages to upgrade its existing Near Earth Network (NEN) polar ground stations to support Ka-band (25.5–27 GHz) operations. Consequently, it becomes imperative that characterization of propagation effects at these NEN sites is conducted to determine expected system performance, particularly at low elevation angles (< 10deg) where spacecraft signal acquisition typically occurs. Since May 2011, NASA Glenn Research Center has installed and operated a Ka-band radiometer at the NEN site located in Svalbard, Norway. The Ka-band radiometer monitors the water vapor line, as well as 4 frequencies around 26.5 GHz at a fixed 10 deg elevation angle. Three-year data collection results indicate good agreement with models and comparable performance to previously characterized northern latitude sites in the United States, i.e., Fairbanks, Alaska. The Svalbard data is used to derive availability results for an upcoming earth-observation mission, JPSS-1, and indicate a requirement of 4 dB of atmospheric attenuation margin necessary to close the link with 99% overall system availability for the expected LEO orbital cycle, as observed from the Svalbard location.**

***Index Terms*—radiometer, RF propagation measurements, Ka-band, polar climate.**

I. Introduction

NASA's architecture for the Near Earth Network (NEN) calls for upgrades to operational Ka-band in the 2018 timeframe to support throughputs of 1.2 Gbps at Low Earth Orbit (LEO)/Middle Earth Orbit (MEO), 150 Mbps at L2, and 25-70 Mbps at distances ranging from LEO to the Moon [1]. These mission requirements are driven by the manifest of upcoming earth science, lunar robotic, and human exploration missions expected to be launched in the near future [2]. Since 2010, the implementation of these new Ka-band services via the NEN network has been investigated, which includes the characterization of Ka-band propagation effects at the northern polar network located in Svalbard. Ka-band data at these northern latitudes and low elevation angles is limited, and a concerted effort was undertaken by NASA to characterize the Svalbard site to determine the expected link margins and system availability for the imminent Ka-band communications system upgrades. Since May 2011, NASA Glenn Research Center (GRC), in collaboration with Goddard Space Flight Center (GSFC) and Kongsberg Satellite Services (KSAT), has installed and operated a Ka-band radiometer at the Svalbard site. Svalbard was chosen as the appropriate site for two primary reasons: (1) Svalbard will be the first site to be upgraded to Ka-band operations within the NEN Polar Network enhancement plan, and (2) there exists a complete lack of Ka-band propagation data at this site (as opposed to the Fairbanks, AK NEN site, which has 5 years of characterization collected during the Advanced Communications Technology Satellite (ACTS) campaign). Herein, we discuss the data processing and provide the three-year measurement results from the ongoing Ka-band propagation characterization campaign at Svalbard, Norway. Comparison of these results with the ITU models and existing ERA profile data indicates very good agreement when the 2010 rain maps and cloud statistics are used. Finally, the Svalbard data is used to derive the expected atmospheric margin requirements for this site necessary to maintain total system availability levels for the upcoming Joint Polar Satellite System (JPSS) launch in the 2017/2022 timeframes.

II. Svalbard Experiment Description

The NASA Ka-band propagation terminal, designated SG61, is located at the east end of the Svalbard NEN complex as shown in the aerial photograph in Figure 1. The operational equipment at SG61 consists of a Radiometrics PR-2330 Polarimetric Radiometer and a weather station, which are shown in Figure 2 (a) and (b), respectively.

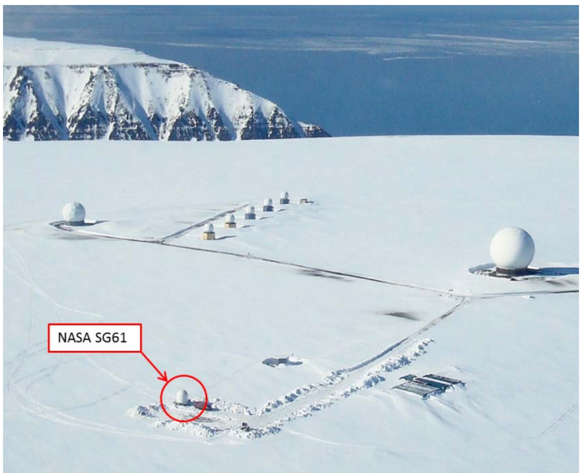
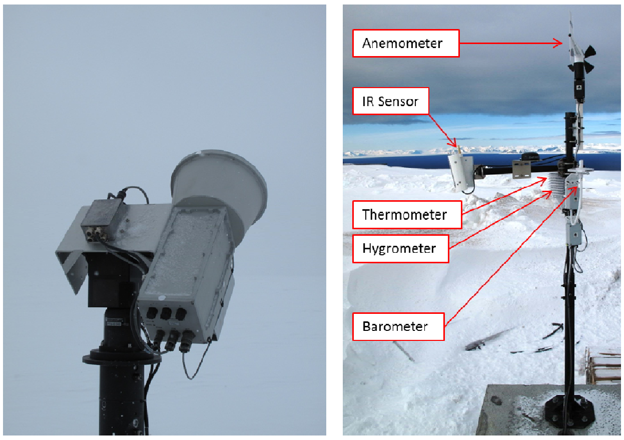


Figure 1. Aerial photograph of the Svalbard NEN site showing the location of SG61.



(a) **(b)**

Figure 2. (a) Photograph of Radiometrics PR-2330 Polarimetric Radiometer, and (b) photograph of weather station at SG61.

A. SG61 Hardware Description

The Radiometrics PR-2230 is a high-resolution, single polarization, 22 to 30 GHz radiometer with a 3-degree half-power beamwidth (HPBW) antenna, optimized for high performance in harsh, extreme environments. An internal Baseband Processor controls the radiometer state sequence and timing, maintains thermal stability, collects and processes all data, and communicates with the user via two serial ports. An internal accelerometer, in tandem with the pan and tilt positioner, provides pointing accuracy to 0.1-degrees. System gain and receiver temperature are measured continuously and applied to the transfer function in real time to generate accurate calibrated brightness temperatures with no lengthy calibration interruptions. A 4 point calibration and non-linear transfer function are used to compensate for small, finite system linearity errors [3]. A block diagram of the PR-2230 radiometer is shown in Figure 3 and a summary of the operational specification of the unit is provided in Table 1 [3].

The PR-2230 can be programmed to observe multiple channels (up to 21 unique frequencies) over the 22-30 GHz band, and records the measured power at each frequency sequentially through the Digital Intermediate Frequency (IF) Module swept controller (see Figure 3). A pre-detection channel bandwidth of 300 MHz and a 1 sec. integration time provide a brightness temperature resolution of <0.5 K. An infrared (IR) sensor is also affixed to the radiometer for cloud detection along the direction of observation.

The local weather station consists of a suite of Young sensors measuring local temperature, pressure, humidity, and wind velocity, as well as a secondary, zenith-pointing ClarityII IR sensor which measures cloud base temperature to identify the presence of clouds. The consistent subzero temperatures at the site makes rain rate measurements very unreliable, therefore, a tipping bucket was not included as part of the weather measuring instruments. However, the PR-2230 system includes a Viasala WXT520 which is capable of crudely differentiating between periods of rain and non-rainy conditions.

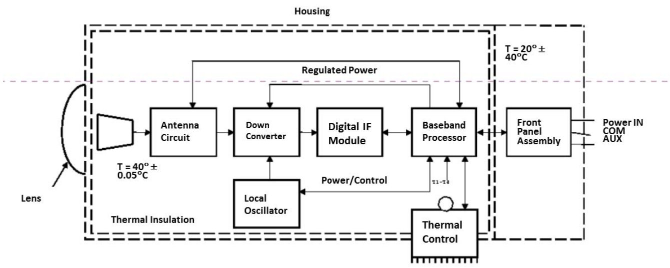


Figure 3. Block diagram of the Radiometrics PR-2230 Polarimetric Radiometer.

Table I. Performance Specifications of Radiometrics PR-2230 Polarimetric Radiometer [3].

Parameter	Specification
Calibrated Brightness Temperature Accuracy	0.2 + 0.002*|Tref – Tsky| K
Long Term Stability	< 1.0 K/0.5yr (typ.)
Resolution (dependent on integration time)	0.1 to 1K
Integration Time (user selectable in 10 msec increments)	0.01 to 2.5 sec
Brightness Temperature Range	0 – 400K
Antenna System Optical Resolution and Side Lobes	3° / -24dB
Frequency Agile Tuning Range	22.0 – 30.0 GHz
Standard Calibrated Channels	21
Pre-detection Channel Bandwidth	300 MHz
Surface Sensor Accuracy	
Temperature (-50 to 50 °C)	0.5 °C @ 25 °C
Relative Humidity (0-100%)	2%
Barometric Pressure (800 to 1060 mb)	0.3 mb
Infrared Thermometer (IRT)	(0.5 + 0.007*ΔT) °C
Calibration Systems	
Primary Standards	TIP method
Operational Standards	Noise Diode + ambient Black Body Target

B. Radiometer Operations

As part of normal operations, the PR-2230 Polarimetric Radiometer monitors 4 channels across the operational Ka-band bandwidth at 25.5, 26, 26.234, and 26.5 GHz, as well as two channels to measure the water vapor line at 22.234 and 30 GHz, with a 1 second integration time at each frequency. Due to the sequential nature of the swept downconverter, brightness temperatures are recorded at each frequency with a repetition rate through the full observation spectrum of approximately 10 seconds. Every 10 minutes, a noise diode calibration is performed to maintain transfer function linearity. This results in an absolute radiometer resolution of < 0.5 K. Sky tip calibrations are performed daily at 0:03 GMT, wherein 4 elevation angles are measured at each of two opposing azimuth directions (to smooth out atmospheric inhomogeneities). The tip curve calibrations are then applied in post-processing to calibrate the recorded brightness temperature measurments.

In accordance with the NEN Ka-band planning team's requirement of low elevation angle observations, the radiometer elevation angle has been fixed to 10° since December 2011.

III. MEASUREMENT RESULTS

A. Data Calibration and Ground Bias Removal

The raw voltage measurements by the radiometer are converted to sky temperature emission via the radiometer transformation coefficients and recorded to file as the Level 1 Observables. However, occasionally the radiometer will record erroneous data due to system instabilities, operator interventions, or physical issues (i.e., ice formation on the antenna) throughout a given day. Furthermore, ground emission may also introduce a bias into the radiometer measurement that must be removed in post processing. As such, a procedure was developed to correct and/or remove bad data. The data calibration procedure for removing bad points was defined in two steps. This process is performed on a monthly basis for automatic removal and a daily basis via manual inspection.

- An automatic approach which identifies and flags rms brightness temperature thresholds which exceed 10 K over a 1-min block period, as well as removes uncorrelated events on the channels,
- A manual approach to visually inspect and isolate anomalous data.

Fig. 5 shows an example time series where bad data was identified by the data calibration routine. Fig. 6 shows a scatter plot for the 22/30 and 26/30 channels for a particular month where bad data was recorded and subsequently removed (bad data is shown as red points).

To identify the presence of ground emission, a comparison of the complete calibrated brightness temperature scatterplots with Leibe's MPM93 model [4] using ERA40 and ERA Interim profiles for the Svalbard location was performed on a monthly basis. Figure 7 shows the scatterplot comparisons for the measured radiometer data and the derived model results for the month of June 2012. From the plot, it is evident that ground emission at the low elevation angle is indeed present and biasing all channels. Based on the bias conditions, an assumed main beam efficiency of 96% for the 26.5 and 30 GHz channels and 94% for the 22.234 GHz channel results in the proper correction of the ground emission bias term. The slightly worse performance at the lower frequency channel is expected due to the common lens-based antenna utilized for the wide frequency range. Ground emission correction (ΔT) is applied based on the local air temperature (T_{GND}) and the main beam efficiency (H) using the relation [5],

$$\Delta T = \frac{(1-H)T_{GND}}{H}$$

Once the correction is applied, good agreement between the radiometer measurements and the historical profile-based model is achieved, as indicated in Figure 8.

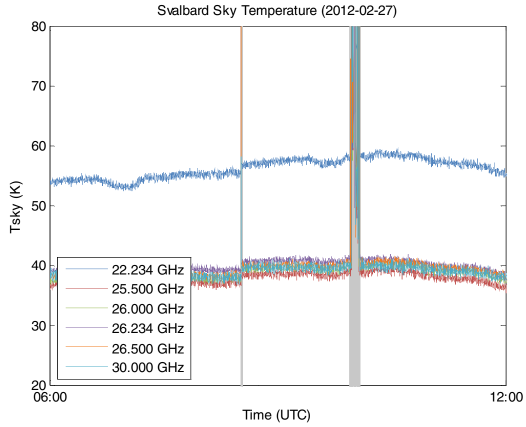


Figure 5. Radiometer time series with bad blocks of data identified by blue bars.

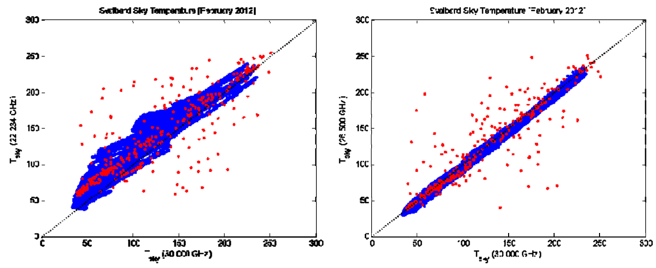


Figure 6. Scatter plot of 22.234 and 30 GHz channels (left) and 26.5 and 30 GHz channels (right) for the month of February 2012. Good data is shown in blue and identified bad data points are shown in red.

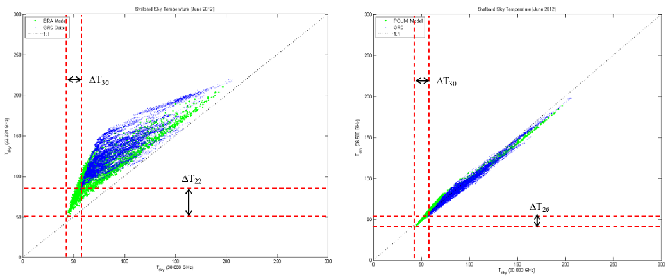


Figure 7. Scatter plot of calibrated 22.234 and 30 GHz channels (left) and 26.5 and 30 GHz channels (right) for the month of June 2012, indicating the presence of a bias on all channels

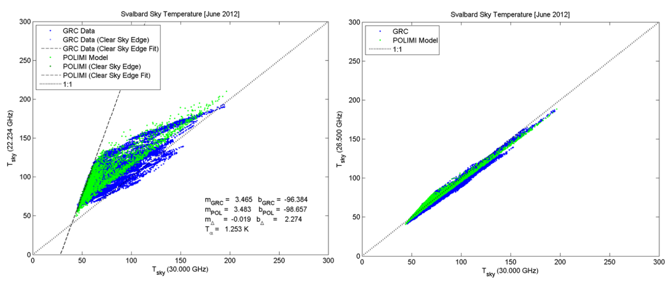


Figure 8. Scatter plot of calibrated 22.234 and 30 GHz channels (left) and 26.5 and 30 GHz channels (right) for the month of June 2012 with bias removed assuming 96% main beam efficiency (for 26.5/30 GHz) and 94% (for 22.234 GHz) channels.

B. *Three-Year Statistics*

The complementary cumulative distribution functions (ccdf) of the surface temperature, pressure, and relative humidity from 2012-2014 are provided in Figs. 9-11, respectively. Fig. 12 shows the ccdf of the sky brightness temperature at the downlink frequency of interest for future Ka-band direct-to-earth systems, 26.5 GHz.

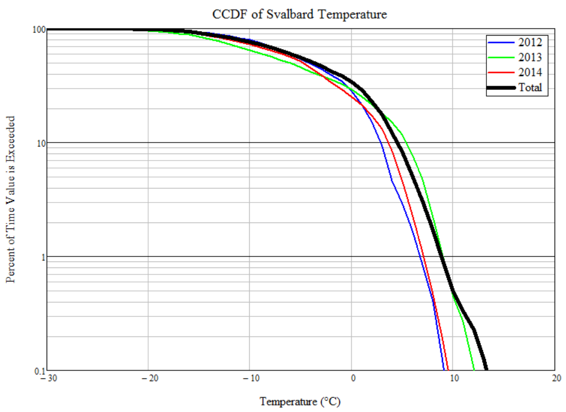


Figure 9. CCDF of surface temperature at Svalbard from 2012-2014.

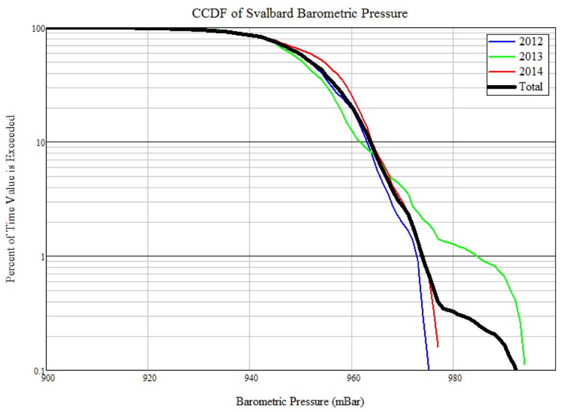


Figure 10. CCDF of surface pressure at Svalbard from 2012-2014.

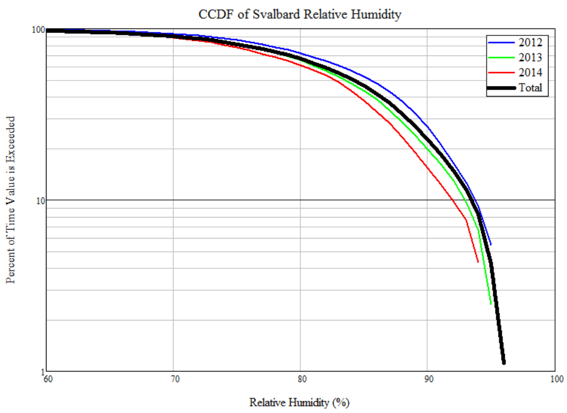


Figure 11. CCDF of surface relative humidity at Svalbard from 2012-2014.

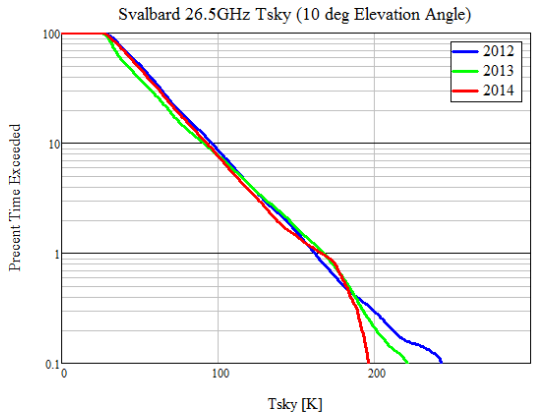


Figure 12. CCDF of sky brightness temperature at 26.5 GHz at Svalbard from 2012-2014.

From the sky brightness temperature, attenuation, in dB, is derived using the simplified radiative transfer relation,

$$A = 10log\left(\frac{T_M - T_C}{T_M - T_B}\right)$$

where T_C is the cosmic background temperature, taken to be 2.75 K, T_B is the measured brightness temperature, and T_M is the atmospheric mean radiating temperature, which, based on historical data at Svalbard, is taken to be a constant 275 K.

For the purposes of NASA's Near Earth Network Ka-band planning team, we are interested in the expected performance of ground systems operating at Ka-band at low elevation angles (< 10°) where initial link acquisition occurs with polar orbiting LEO satellites. The ccdf of the yearly and average radiometer-derived attenuation at Svalbard at 10° elevation angle is shown in Figure 13 for the primary frequency of interest, 26.5 GHz. Also plotted in Figure 13 is the ITU-R model results, taking into account the attenuation contributions from gaseous absorption, cloud attenuation, and rain attenuation, utilizing the 2010 rain rate maps and cloud statistics, [2]. The ITU model shows good agreement when compared to measurements at Svalbard.

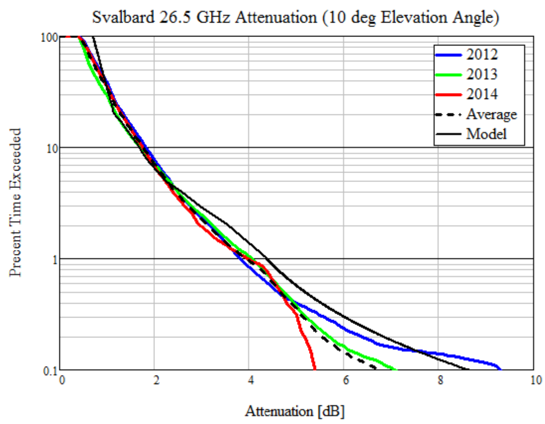


Figure 13. CCDF of radiometer-derived attenuation at Svalbard at 10° elevation angle for 2012-2014 compared with ITU-R model

IV. Preliminary Link Budget Estimates for JPSS

The intended use of this data is to help define the requirements for future systems which will utilize Svalbard as a ground station at Ka-band. The Joint Polar Satellite System (JPSS) is one such mission expected to launch a series of satellites in the 2017/2022 timeframe and which can directly benefit from the propagation data being measured at this site. To determine the margin requirements for the JPSS satellite, ITU-R Recommendation P.618 is implemented for determining the joint distribution taking into account the expected distribution of elevation angles [2]. The probability density function (pdf) for the elevation angles for the expected orbit is necessary to estimate the necessary margin for this low earth orbiting (LEO) spacecraft, and is shown in Fig. 14. Based on this distribution, weighting of the attenuation predictions are performed following ITU-R Recommendation P.618 to derive an estimated ccdf for the JPSS-1 satellite. A comparison of the expected atmospheric attenuation for a fixed case 5 deg elevation angle and the conditions which take into account the full LEO orbit at Svalbard are shown in Fig. 15. Based on this analysis, a link margin requirement of approximately 4 dB is necessary to maintain 99% total link availability at Svalbard over the proposed LEO orbital cycle. Note that this does not include effects due to scintillation due to the limitations of the radiometer system. The final ground system specifications will be necessary to determine the impact of this phenomenon. This differs from the planned 99% availability margin requirement of 11.7 dB, which was derived based upon signal acquisition at a fixed 5 deg elevation angle for worst case conditions without considering the distribution of elevation angles during a given pass.

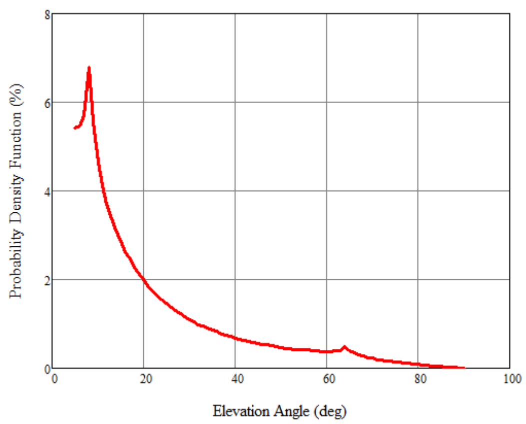


Figure 14. PDF of elevation angles for the expected LEO cycle of JPSS-1.

V. Conclusions

Earth- and space-science missions in the foreseeable future will require Ka-band communications to support their extremely high data rate requirements, and NASA is already planning ahead to upgrade the existing infrastructure to support Near Earth operations, particularly for low earth orbiting polar satellites. Part of this initiative involves determining the system specifications necessary to maintain a given level of availability, which is highly dependent on the propagation characteristics of the atmosphere. For the past 3 years at the polar NEN site in Svalbard, NASA GRC has been measuring Ka-band propagation data at low elevation angles and has identified a link margin requirement of approximately 4 dB (not included scintillation losses) to accommodate a 99% availability level at the Svalbard, when the full LEO orbit is taken into account. This measured attenuation agrees extremely well with that predicted by the ITU models. Based on the planned 11.7 dB link margin for the JPSS-1 satellite, link acquisition at a 5 deg elevation angle is expected to occur with 99.7% availability, with an overall system availability of approximately 99.98%. Reducing this margin by 7 dB for future missions should be able to provide the necessary conditions to maintain system link availability for the target 99% availability level.

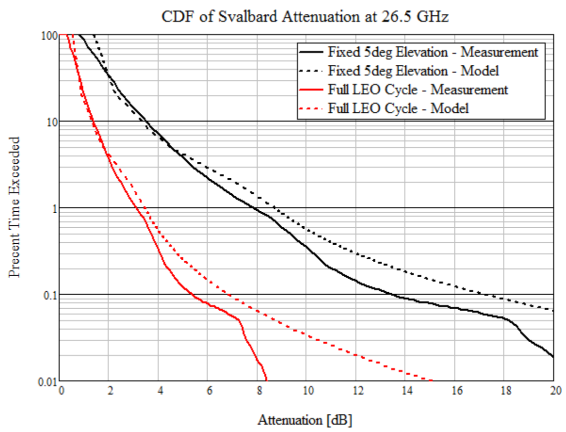


Figure 15. CCDF comparing fixed 5 deg elevation angle acquisition availability and full LEO orbital cycle link availability. Note that when the LEO orbit is taken into account, an improvement of approx. 5 dB in the atmospheric link margin is realizable.

Acknowledgements

The authors wish to acknowledge the useful comments from Antonio Martellucci, Laurent Castanet, Carlo Riva, and Lorenzo Luini for their help in assessing the validity of the radiometer data, and particularly to Lorenzo's for providing the ERA40/ERA Interim model results for comparisons with the radiometer measurements.

References

[1] Space Communications and Navigation Network Architecture Definition Document: Volume 1, Rev. 2, Oct. 2011.

[2] Recommendation ITU-R P.618-10, "Propagation data and prediction methods required for the design of Earth-space telecommunication systems," Oct. 2009.

[3] Radiometrics Corporation PR Series Radiometer Handbook, Chapter 3, p.1-3, 2011.

[4] H.J. Liebe, G.A. Hufford, M.G. Cotton, "Propagation modeling of moist air and suspended water/ice particles at frequencies below 1000 GHz," Proc. NATO/AGARD Wave Propagation Panel, 52nd meeting, No. 3/1-10, Mallorca, Spain, 17-20 May 1993.

[5] F.T. Ulaby, R.K. Moore, A.K. Fung, Microwave Remote Sensing: Active and Passive; Volume I: Microwave Remote Sensing Fundamentals and Radiometry, pp. 456, Addison-Wesley, Reading, MA